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Forest-floor temperatures and soil moisture across riparian zones on first- to third-order headwater streams in southern New England, USA

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ABSTRACT

Riparian zones along forest streams in the western United States have been repeatedly shown to be floristically and climatically different from adjacent upland forest, and to be important contributors to forest biodiversity. Similar evidence for the presence or function of riparian zones is lacking for forests of the northeastern U.S. We conducted seasonal surveys of forest-floor temperature and soil moisture across 30-m riparian transects on first- to third-order streams in southern New England. We were unable to detect any effect of distance from the stream channel on either temperature or soil moisture. These preliminary results indicate the absence of a unique riparian forest-floor microclimate within 30 m of low-order streams in southern New England. While this study failed to identify a distinctive riparian microclimatic zone, protection of a riparian buffer during forestry operations or other disturbance is essential for the protection of forest streams and their resources and the maintenance of forest biodiversity.

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1. Introduction

Riparian zones along forest streams have been shown to be important in structuring vertebrate communities and maintaining biodiversity (Sabo et al., 2005). However the bulk of evidence in support of this comes from studies in more arid western forests (e.g., forest-floor invertebrates [Rykken et al., 2007b], amphibians [Olson et al., 2007]), where cool, moist microclimatic conditions in riparian zones are strongly different from those in adjacent upland forest (Rykken et al., 2007a).

The evidence of distinctive riparian zones in more humid eastern forests is less persuasive. Studies have failed to identify differences in small mammal communities in North Carolina (Laerm et al., 1999) and West Virginia (Osbourne et al., 2005), soricids in West Virginia (Ford and Rodrigue, 2001), or eastern boreal conifer bird communities (Whitaker and Montevecchi, 1997; Meiklejohn and Hughes, 1999) between riparian (stream side) and upland forest. The authors ascribe these findings to a lack of a clear riparian vegetative community along low-order streams in these forests. Conversely, Bub et al. (2004) found avian diversity to be greater in riparian (<25 m of first- and second-order streams) than upland forests in Michigan's Upper Peninsula; also finding that riparian forests were conifer dominated and uplands, deciduous dominated. Lowe and Bolger (2002) and Lowe et al. (2005) identified the importance of riparian-forest vegetation to spring salamanders (*Gyrinophilus porphyriticus*) in New Hampshire. However, the effect was simply due to the presence of forest, the reduction in sedimentation, and the increase in terrestrial, invertebrate prey, and not to any unique riparian forest condition.

The occurrence of a biologically unique riparian zone is due in part to periodic-flooding disturbance (Packman and Hughes, 1995) and to climatic and soil-moisture influences of the stream (Hagan and Whitman, 2000; Moore et al., 2005). Forest microclimate influences ecological processes, such as plant regeneration and growth, soil respiration, nutrient cycling, and wildlife habitat selection (Chen et al., 1999). Riparian microclimate and stream temperatures are closely interconnected and influence habitat conditions in and near streams (Moore et al., 2005). The presence of a microclimatic riparian-upland gradient has been identified in western forests, with the stream effect extending out to 47 m for air and soil temperatures and 62 m for surface temperatures and humidity (Brosofske et al., 1997). However, Danehy and Kirpes (2000) identified a riparian effect on relative humidity within only 10-m of stream edge in eastern Oregon and Washington states. No such delineation has been made for eastern forest riparian zones.

In the absence of science-based criteria and standardized definitions, riparian buffers are variously defined and determined. Protective regulations typically use an arbitrary distance from a stream, or a minimum distance that is extended based on slope (e.g., Massachusetts cutting practices regulations [M.G.L. Ch. 132]

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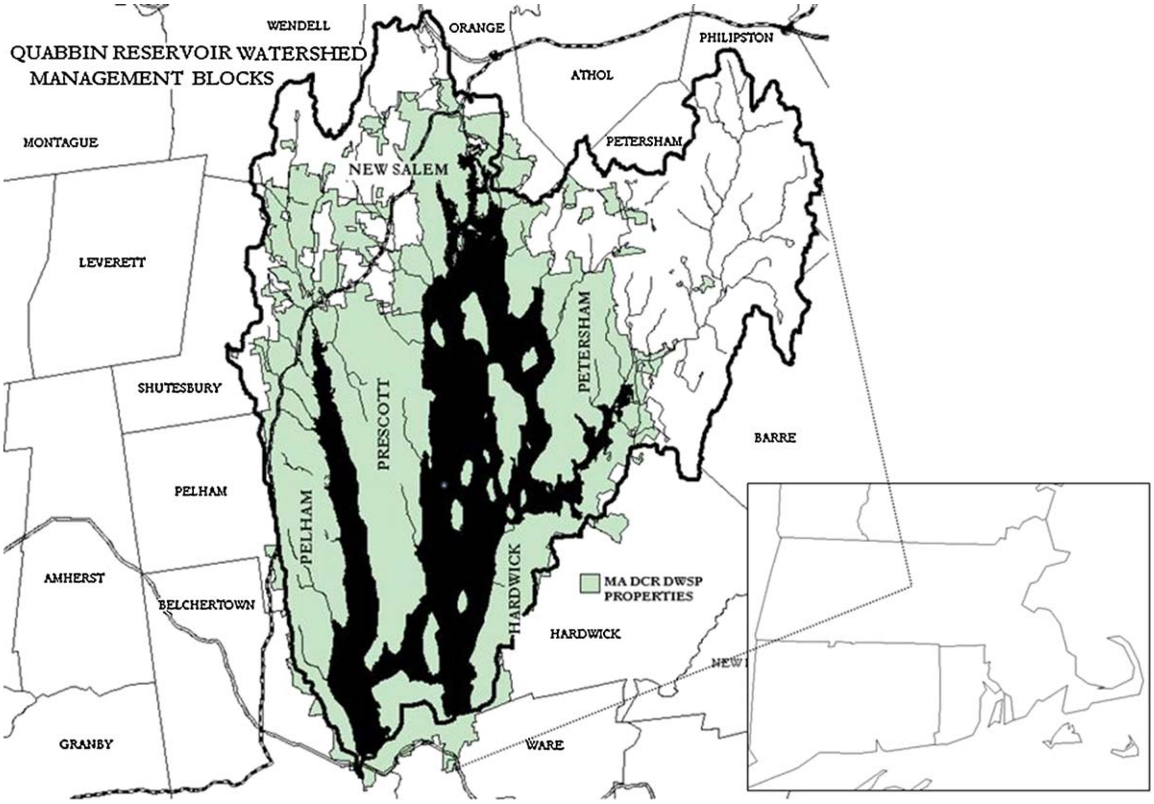

Fig. 1. Location of Quabbin Reservoir watershed in central Massachusetts, southern New England, USA.

set a minimum filter strip width of 50-feet [15.2 m], which increases by 40 feet [12.2 m] with every 10% increment in slope). In some instances, riparian zones may be defined by the plant community composition (Hagan et al., 2006) or amphibian richness and abundance (Perkins and Hunter, 2006). Crawford and Semlitsch (2007) recommend a riparian buffer zone of almost 93 m on southern Appalachian "headwater" (undefined) streams to protect stream-breeding salamanders. However, there is no consensus as to the most effective and efficient buffer widths that protect stream and riparian ecosystems (Chen et al., 1999). Distinctive microclimatic conditions may indicate riparian zones (Chen et al., 1999), but this is largely untested in the northeastern U.S.

The objectives of this study are to quantify spatial patterns in forest-floor temperature and soil moisture (e.g., microclimate) across riparian-upland gradients along low-order (e.g., first to third order) streams in southern New England. Comparisons of microclimate were made among distances from stream centers to test for the extent of the stream effects on microclimate by stream order. These data also allowed for the comparison of stream water and air temperatures by season and stream order. Relationships between air and stream water temperatures have been investigated to assess the use of air temperature as a surrogate for stream water temperature in climate change assessments (Pilgrim et al., 1998; Mohseni and Stefan, 1999).

2. Methods

2.1. Study area and sites

The study was done on the watershed of the Quabbin Reservoir in central Massachusetts. The Reservoir was created by the construction of the Winsor Dam (long: 72°20′39″, Lat: 42°16′50″) in the late 1930s (Kyker-Snowman et al., 2007). The Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection (MA DCR) manages these public lands. All streams that flow into the Reservoir (subwatersheds; Kyker-Snowman et al., 2007, p. 143) were given unique identification numbers. Each stream was tracked to its origin on 1:25,000 U.S. Geological Survey topographic maps and each tributary was given a related, unique identification number (e.g., 56.4.1 identifies the first sub-tributary of the fourth tributary of subwatershed number 56). Each uniquely numbered stream segment, main stem or tributary, was classified by Strahler stream order (Strahler, 1952).

Study stream segments were chosen from the three western and central Management Blocks to insure wide spatial dispersal (Fig. 1). The eastern Petersham and Hardwick Management Blocks are too distant for efficient access and were not included in the study. Stream segments were randomly chosen from the full list of stream segments in each Management Block. Stream segments were chosen by stream order; one first-, second-, and third-order stream. A separate set of three stream segments from each Management Block was randomly chosen for a spring, summer, and fall sampling session, for a total of 27 study stream segments (Table 1). Selected stream segments were visited to ensure that the riparian area had not been recently harvested or otherwise disturbed. If a selected stream had been disturbed, it was replaced with the subsequent random selection. The upstream stream length and basin area for each stream segment were obtained using the website StreamStats for Massachusetts http://water.usgs.gov/osw/streamstats/massachusetts.html.

Each selected stream segment was accessed from the lowest downstream road crossing or from a point along a road closest to the stream channel. From each access point, a starting point was randomly located between 50- and 100-m upstream of the access point. Occasionally the sampling point had to be located downstream of the access point when the upstream location was

Table 1
List of study stream segments by order, session, and Management Block and inclusive dates of microclimatic surveys, Quabbin Reservoir watershed, Massachusetts.

Season	Order	Drainage	Subbasin	Management Block	Data loggers on	Data loggers off
Spring	1	Moosehorn Brook	75.3	New Salem	5 June	12 June
Spring	2	Rocky Run Brook	69	New Salem	5 June	12 June
Spring	3	Hop Brook	78	New Salem	5 June	12 June
Spring	1	Gulf Brook	51.3	Pelham	28 May	4 June
Spring	2	Gulf Brook	51	Pelham	6 May	14 May
Spring	3	Atherton Brook	47	Pelham	28 May	4 June
Spring	1	Underhill Brook	45.3	Prescott	15 May	22 May
Spring	2	Egypt Brook	49	Prescott	15 May	22 May
Spring	3	Dickey Brook	57	Prescott	15 May	22 May
Summer	1	Manning Brook	75.1	New Salem	24 July	31 July
Summer	2	Moosehorn Brook	75	New Salem	24 July	31 July
Summer	3	Mdl Br Swift River	76	New Salem	24 July	31 July
Summer	1	Purgee Brook	50.2	Pelham	7 July	14 July
Summer	2	Purgee Brook	50	Pelham	7 July	14 July
Summer	3	Atherton Brook	47	Pelham	7 July	14 July
Summer	1	Dickey Brook	57.4	Prescott	15 July	22 July
Summer	2	Dickey Brook	57.5	Prescott	15 July	22 July
Summer	3	Dickey Brook	57	Prescott	15 July	22 July
Fall	1	Hop Brook	78.4	New Salem	14 October	21 October
Fall	2	Hop Brook	78.3	New Salem	14 October	21 October
Fall	3	"Canada Brook"	66	New Salem	14 October	21 October
Fall	1	Briggs	48	Pelham	23 October	30 October
Fall	2	Cadwell	60	Pelham	23 October	30 October
Fall	3	Atherton Brook	47	Pelham	23 October	30 October
Fall	1	Dickey Brook	57.51	Prescott	3 October	10 October
Fall	2	Dickey Brook	57.1	Prescott	3 October	10 October
Fall	3	Dickey Brook	57	Prescott	3 October	10 October

unavailable, generally due to the presence of a beaver pond or meadow.

2.2. Field methods

From the starting point along the stream channel, five sampling locations were installed, starting at the center of the stream channel and proceeding perpendicular to the stream channel into the adjacent forest. The sampling locations were the stream channel, the stream bank, and at 5-, 15-, and 30-m from the stream bank. The 15 m location is the upland border of the regulatory riparian buffer strip in Massachusetts and the 30 m location is well within the unregulated, upland forest. The installation of the sampling locations left or right of the stream channel, while facing upstream, was determined on the flip of a coin.

Elevations of the 5-, 15-, and 30-m locations relative to the steam bank were calculated using percent slope measured with a clinometer (Table 2). The elevations of the 5-, 15-, and 30-m survey locations were minimally variable among stream order ($F_{df=2,96}$ = 1.349, p = 0.264). The average elevations of the 5- and 15-m survey locations above the bank elevation were highest for the first-order stream segments and lowest for the third order, while the elevations of the 30-m survey locations were highest for the second-order stream segments. Elevations among survey locations followed the logical progression from Bank to 30-m: average bank height – 0.73 m, 5-m elevation – 1.15 m; 15 m – 1.92 m; and 30 m – 3.09 m (Table 2). These differences were consistent ($F_{df=2,96}$ = 20.5, $p < 0.001$). In post-hoc, pairwise comparisons, bank heights differed from 15-m location elevations (p = 0.001) and 30-m location elevations ($p < 0.001$); 5-m location elevations differed from 30 m ($p < 0.001$); and 15-m location elevations differed from 30 m (p = 0.004).

At each terrestrial location, iButton Hydrochron® (DS1923, Dallas Semiconductor Corporation, 4401 South Beltwood Parkway, Dallas, TX 75244) and HOBO® (Onset Computer, 470 MacArthur Blvd., Bourne, MA 02532) data loggers were used to measure, respectively, soil and air temperatures. Soil temperatures were measured at interface of organic- and mineral-soil horizons and air temperatures at 1 m above the ground surface with the HOBO attached to a wooden stake, oriented north, and shaded with a painted piece of aluminum flashing. In the stream channel, a dual channel HOBO was used to simultaneously measure air and stream-water temperatures. Both brands of data loggers are accurate to about ±0.05 °C. The devices were programmed to record temperatures hourly and were in-place at each location for an 8-day/7-night sampling period (Table 1). Inter-logger accuracy was not compared prior to their use.

An Aquaterr® M-300 soil moisture meter (Aquaterr Instruments and Automation, 1685 Babcock Street #A, Costa Mesa, CA 92627) was used to measure soil moisture three times during each survey period (at the beginning when the temperature loggers were installed; at the end when the loggers were removed; and in-between when the vegetation survey was done) at each terrestrial location. The Aquaterr "is a capacitance probe which measures the dielectric constant of the soil-air-water combination" (Aquaterr Instruments Moisture Meter Guidebook: For Aquaterr Instruments Series 200 and 300, Aquaterr Instruments and Automation, 1685 Babcock Street #A, Costa Mesa, CA 92627). The published accuracy of the meter is ±1.5%. The meter was calibrated by immersion in stream water prior to each site survey. Soil moisture was measured at a depth of 12–15 cm at five points at each location, parallel to the stream channel. The soil was tamped down around the probe by foot before a reading was taken. The five measurements were averaged by location for each of the three surveys.

Overstory canopy cover and closure were measured at each location using GRS ("moosehorn") and concave mirror densiometers (Cook et al., 1995; Jennings et al., 1999; Paletto and Tosi, 2009), respectively. The two techniques measure cover as "the area of the ground covered by a vertical projection of the canopy" and closure as "the proportion of the sky hemisphere obscured by vegetation when viewed from a single point" (Jennings et al., 1999). Overstory cover was measured in the four cardinal directions, originating from the location stake. Overstory canopy closure was recorded at 10 one-meter intervals along eight transects oriented at 45° intervals from the survey location. Vegetation composition and structure were sampled on nested,

Table 2
Basin and stream channel dimensions and upland elevations by order, Quabbin Reservoir watershed, Massachusetts, 2008.

Order	Drainage	Sub-basin number	Basin dimensions (StreamStats)			Channel dimensions			Upland location elevations (m) above Bank		
			Basin area (km^2)	Stream length (km)	Channel width (m)	Bank height (m)	Bank width (m)	Floodprone width (m)	5 m	15 m	30 m
1	Underhill Brook	45.3	0.75	0.74	3.1	0.2	0.3	0.8	1.7	1.8	2.1
1	Briggs	48	1.42	1.71	1.7	0.8	1.4	0.7	0.05	0.3	0
1	Purgee Brook	50.2	0.98	1.43	8.2	1.05	1.1	24.4	0.2	0.45	1.2
1	Gulf Brook	51.3	0.23	0.29	1.3	0.35	0.5	6.3	0.25	0.75	0
1	Dickey Brook	57.4	0.34	0.89	2.2	0.2	0.4	0.9	1.2	2.55	2.7
1	Dickey Brook	57.51	0.21	0.58	1.2	0.15	0.4	1.4	0.3	0.6	1.8
1	Manning Brook	75.1	1.35	1.37	2.5	0.5	1.2	5.1	0.15	1.5	2.1
1	Moosehorn Brook	75.3	1.22	0.21	2.4	0.4	0.6	3.8	1.3	4.2	6.9
1	Hop Brook	78.4	0.75	0.60	2	0.3	0.5	26.8	0.25	0.75	1.5
Average			0.81	0.87	2.73	0.44	0.71	7.80	0.60	1.43	2.03
2	Egypt Brook	49	2.38	3.65	3.1	0.3	0.5	4.6	0.6	1.05	1.5
2	Purgee Brook	50	6.99	10.32	1.6	0.42	0.2	7.2	0.2	0.45	1.8
2	Gulf Brook	51	1.92	2.27	5.6	2.7	4.3	1.2	0.6	1.05	1.8
2	Dickey Brook	57.1	2.93	4.36	2.6	0.7	0.9	2.1	1.1	3.9	6.3
2	Dickey Brook	57.5	0.93	2.38	2.9	0.4	0.3	27	0.45	0.75	1.5
2	Cadwell	60	5.54	6.52	4.1	0.85	0.6	40.5	−0.1	0	−0.6
2	Rocky Run Brook	69	3.06	4.70	2.1	0.8	1	3.3	1.05	2.1	5.1
2	Moosehorn Brook	75	2.36	2.33	2.3	0.2	0.3	22.8	0.4	0.3	3.3
2	Hop Brook	78.3	2.43	3.17	4.2	0.4	0.6	2.7	0.55	1.8	5.4
Average			3.17	4.41	3.17	0.75	0.97	12.38	0.54	1.27	2.90
3	Atherton Brook	47	5.72	9.01	5.8	0.4	0.3	21.1	0.25	0.3	1.8
3	Atherton Brook	47	4.71	8.06	6.6	0.6	1	11.9	0.4	2.1	4.5
3	Atherton Brook	47	6.73	10.57	5.5	0.46	0.3	4.3	0.6	1.65	3.6
3	Dickey Brook	57	10.75	20.60	5.9	1.1	0.2	35.5	0.1	0.3	0
3	Dickey Brook	57	6.55	13.90	2.9	1.2	1.5	17.6	0.3	0.15	1.2
3	Dickey Brook	57	6.32	13.44	5.3	0.3	0.5	8.6	0.4	1.8	2.1
3	“Canada” Brook	66	10.00	11.86	5.7	0.5	0.6	2.3	0.85	2.7	5.7
3	Mdl Br Swift River	76	11.37	10.78	4.3	0.5	1.7	5.5	0.6	1.05	2.1
3	Hop Brook	78	14.17	21.73	11.2	1.3	3	28	0.3	0.3	0.9
Average			8.48	13.33	5.91	0.71	1.01	14.98	0.42	1.15	2.43

circular plots (0.001 ha for seedling-sized [<2.5 cm diameter at breast height {dbh}; >30 cm tall]; 0.01 ha for woody stems >2.5 cm dbh and percent ground cover and downed, woody debris cover), centered on the location stake. A single vegetation survey was done for the Bank and 5-m locations given their close proximity.

Ambient air temperature and precipitation data were provided by the Belchertown NOAA station, operated by the MA DCR and located at the Winsor Dam.

2.3. Analysis

Minimum and maximum daily water, air, and/or soil temperatures were identified and mean daily temperatures were calculated for each individual data logger. Average minimum, maximum, and mean daily temperatures were calculated over each 8-day survey for all sessions, stream orders, locations, and replicates (Management Blocks). The daily range in stream water temperature was calculated as the difference of the daily minimum and maximum water temperatures. The effects of distance from the stream channel (riparian location) and of stream order on air and soil temperature, percent soil moisture, and vegetative structure and of stream order on water temperatures were analyzed using analysis of variance. Soil moisture data were analyzed using repeated measures ($n = 3$) analysis of variance. For significant ($p \leq 0.05$) effects, pairwise differences were tested using Tukey's Difference Test. Vegetation survey data were summarized for stream order and riparian location. Composition was characterized by importance values, based on relative frequency, density, and dominance (Mueller-Dombois and Ellenberg, 1974, pp. 118–120). All percent measures were arcsine transformed prior to analysis.

3. Results

3.1. Stream segment and vegetation characteristics

As expected, the physical characteristics of the study stream segments differed by order. The average basin area and stream length above the sampling point increased with order, as did channel width at the sampling point. The average basin area of first-order streams above the survey point was 0.81 km^2 and average stream length was 0.87 km (Table 2). For second-order streams, the same statistics were 3.17 km^2 and 4.41 km, respectively, and for third-order streams, 8.48 km^2 and 13.33 km. Average channel width at the survey point by stream order was 2.73 m (first), 3.17 m (second), and 5.91 m (third). Bank dimensions were more variable, with average bank height of third-order streams less than the average for second-order steams (0.71 m *vs.* 0.75 m, respectively), while the average bank height of first-order streams was 0.44 m. Average bank width increased with stream order.

Vegetation structure was minimally different minimally across stream orders and sampling locations (Table 3). Average basal area of trees >2.5 cm dbh ranged between 22.5 and 59.1 m^2/ha. Basal area differed by stream order ($F_{df=2,72} = 2.588$, $p = 0.082$), with basal area along first order streams differing from that along third order streams (Tukey's HSD = −14.7, $p = 0.068$). Average tree

Table 3
Average vegetation structure and top five species, based on importance value (maximum of 300%), by stream order and riparian location, Quabbin Reservoir watershed, Massachusetts, 2008.[a].

Attribute	Riparian location			
	Channel	Bank/5 m	15 m	30 m
First-order streams				
Basal area (m^2/ha)		40.1	22.5	42.7
Density (1000 s/ha)		5.1	1.7	1.2
Seedling density (1000 s/ha)		16.9	17.2	12.3
Richness (# species)		22	24	21
Importance value (%)		*Acru* (131)	*Acru* (123)	*Pist* (169)
		Pist (123)	*Pist* (98)	*Acru* (89)
		Tsca (93)	*Quru* (59)	*Bele* (52)
		Bele (54)	*Tsca* (59)	*Acsa* (48)
		Acsa (48)	*Prse* (53)	*Vasp* (44)
Canopy cover (%)	98.3	99.8	100	100
Canopy closure (%)		91.6	93.1	90.5
Ground cover (%)		33.4	44.0	40.6
CWD cover (%)		0.9	1.0	1.1
Second-order streams				
Basal area (m^2/ha)		43.2	46.8	41.6
Density (1000 s/ha)		2.2	1.7	2.1
Seedling density (1000 s/ha)		14.9	26.8	22.2
Richness (# species)		18	19	19
Importance value (%)		*Pist* (148)	*Pist* (133)	*Pist* (182)
		Tsca (89)	*Acru* (99)	*Tsca* (88)
		Acru (84)	*Tsca* (80)	*Quru* (68)
		Bele (79)	*Acsa* (56)	*Bele* (66)
		Quru (51)	*Coco* (51)	*Acsa* (59)
Canopy cover (%)	93.6	100	100	100
Canopy closure (%)		96.4	96.4	97.0
Ground cover (%)		23.6	20.4	37.2
CWD cover (%)		0.3	2.1	2.6
Third-order streams				
Basal area (m^2/ha)		59.1	50.9	39.4
Density (1000 s/ha)		1.2	0.9	1.3
Seedling density (1000 s/ha)		7.6	12.4	16.2
Richness (# species)		18	15	21
Importance value (%)		*Tsca* (144)	*Tsca* (185)	*Pist* (112)
		Acru (94)	*Pist* (92)	*Tsca* (112)
		Pist (94)	*Acru* (52)	*Acru* (62)
		Bele (49)	*Bele* (43)	*Quru* (61)
		Fram (38)	*Acsa* (30)	*Fram* (57)
Canopy cover (%)	93.7	100	99.2	100
Canopy closure (%)		96.5	92.0	97.2
Ground cover (%)		20.0	25.8	34.0
CWD cover (%)		0.3	1.7	0.6

[a] Species codes: *Acru* – *Acer rubrum* L. (red maple), *Acsa* – *A. saccharum* Marsh. (sugar maple), *Bele* – *Betula lenta* L. (black birch), *Coco* – *Corylus cornuta* Marsh. (beaked hazelnut), *Fram* – *Fraxinus americana* L. (white ash), *Pist* – *Pinus strobus* L. (eastern white pine), *Prse* – *Prunus serotina* Ehrh. black cherry), *Quru* – *Quercus rubra* L. (northern red oak), *Tsca* – *Tsuga canadensis* (L.) Carr. (eastern hemlock), *Vasp* – *Vaccinium* sp. (low bush blueberry).

density ranged between 0.9 and 5.1 thousand trees per ha. Tree density differed significantly by stream order ($F_{df=2,72} = 3.639$, $p = 0.031$), with density along second-order streams differing from both first- (Tukey's HSD = −863.0, $p = 0.069$) and third (Tukey's HSD = 922.2, $p = 0.048$) order streams. Average seedling density ranged between 7.6 and 26.8 thousand stems per hectare. No effect of either riparian location or stream order on seedling density was found. Average canopy cover and closure were consistently above 90% for all stream orders and survey locations. Canopy cover was the only forest structure attribute that differed by riparian location ($F_{df=3,96} = 4.382$, $p = 0.006$), with cover differing between the channel and each riparian location (Bank/5 m: HSD = 4.511, $p = 0.062$; 15 m: HSD = 4.877, $p = 0.037$; 30 m: HSD = 5.999, $p = 0.006$). Canopy closure differed by stream order ($F_{df=2,72} = 2.759$, $p = 0.07$), due to the difference in closure between first- and second-order streams (HSD = −6.411, $p = 0.063$). The cover of herbaceous and lesser (<2.5-cm dbh) woody-stemmed vegetation averaged less than 50% (Table 3). No effect of either stream order or riparian location on ground cover was found. The cover of coarse woody debris was minimal at these undisturbed, second-growth sites.

The composition of woody-stemmed vegetation was similar among riparian locations and stream orders. Overall, 43 species of trees and shrubs were recorded on all surveys. Thirty species were recorded on first-order stream plots, 27 on second-order, and 25 on third order. Likewise, 30 species were recorded on Bank/5 m riparian locations, 27 at 15 m, and 29 at 30 m. Richness (number of species) by stream order and riparian location ranged between 24 (first order/15 m) and 15 (third order/15 m) (Table 3). Eastern white pine (*Pinus strobus* L.), red maple (*Acer rubrum* L.), and eastern hemlock (*Tsuga canadensis* (L.) Carr.) were the important species overall, based on frequency of occurrence, dominance, and density (Table 3).

3.2. Ambient air temperatures and precipitation

Ambient daily mean air temperatures were lowest during the fall session (average daily mean of 8.2 °C), intermediate in the spring (15.6 °C), and highest during the summer session (22.3 °C) (Table 4). These values were cooler than the 30-year average for the time frame of the spring (18.5 °C) and fall (9.5 °C) sessions and minimally warmer than the comparable long-term average for the

Table 4
Average ambient maximum, minimum, and mean daily air temperatures and total precipitation by seasonal session and sampling week, Quabbin Reservoir watershed, Massachusetts, 2008.

Season	Average daily temperature (°C)				Precipitation (cm)
	Week	Maximum	Minimum	Mean	
Spring	6–14 May	20.2	7.6	13.9	0.46
	15–22 May	16.3	6.0	11.1	0.58
	28 May–4 June	22.6	9.9	16.3	1.35
	5–12 June	27.4	14.9	21.2	2.77
Session mean		21.6	9.6	15.6	1.29
Summer	7–14 July	27.5	16.7	22.1	0.76
	15–22 July	30.2	17.2	23.7	7.47
	24–31 July	26.0	16.0	21.0	9.53
Session mean		27.9	16.6	22.3	5.92
Fall	3–10 October	17.5	2.8	10.1	0.58
	14–21 October	15.1	1.7	8.4	0.28
	23–30 October	12.1	0.1	6.1	5.77
Session mean		14.9	1.5	8.2	2.20

summer (21.8 °C) session. This seasonal pattern was also observed for average daily minimum and maximum temperatures. Total and average weekly precipitation was greatest over the summer session and least over the spring session (Table 4). However, there was considerable variation among weeks in each seasonal session, with exceptionally heavy precipitation over the last two weeks of the summer session and last week of the fall session. Cumulative precipitation over the spring session of the study was considerably less than the 30-year average for the comparable time frame (5.16 cm *vs.* 10.92 cm), slightly less for the comparable fall session (6.6 cm *vs.* 7.79 cm), and considerably greater than the comparable long-term summer session (17.76 cm *vs.* 7.77 cm).

3.3. Channel and riparian zone air temperatures

Over the study, approximately 165 hourly air and soil temperatures were recorded at five locations on three first-, second-, and third-order streams during spring, summer, and fall sessions. Average mean daily air temperature differed among seasons ($F_{df=2,90} = 122.1$, $p < 0.001$). Air temperatures across all stream orders and riparian locations were lowest in the fall survey session, highest in the summer, and intermediate in the spring session (Fig. 2). This pattern corresponded with ambient air temperatures. The average mean daily temperature over the spring session was 15.6 °C (range 3.9–35.0), 22.3 °C (12.2–32.8) for the summer session, and 8.2 °C (−5.3 to 21.0) during the fall session. Neither riparian location nor stream order had an effect on average daily mean air temperatures ($F_{df=4,90} = 0.03$, $p = 0.998$, $F_{df=2,90} = 0.256$, $p = 0.775$, respectively), nor was there an interactive effect of these two factors ($F_{df=8,90} = 0.002$, $p = 1.0$). Seasonal and locational patterns in average daily minimum and maximum air temperatures were the same as for daily mean air temperatures. The results from the analysis of the effects of location and stream order on average daily minimum and maximum air temperatures were also the same as for daily mean temperatures.

3.4. Riparian zone soil temperatures

Hourly soil temperatures were recorded at the Bank, 5-, 15-, and 30-m riparian locations. Patterns in soil temperature tracked those in air temperatures (Fig. 3), but the maximum temperatures were lower and the minimums were higher, for all seasons and stream orders. Season of the year had a large effect on average mean daily soil temperatures (Fig. 3; $F_{df=2,72} = 448.3$, $p < 0.001$). Neither riparian location nor stream order had an effect on average mean daily soil temperatures ($F_{df=3,72} = 0.17$, $p = 0.916$; $F_{df=2,72} = 0.186$, $p = 0.831$, respectively).

3.5. Stream water temperatures

Hourly stream water temperatures were recorded simultaneously with air temperatures. Patterns in water temperature mirrored those of air temperatures, coolest in the fall, warmest in the summer, and intermediate in the spring (Fig. 2). Stream water temperatures were strongly affected by season ($F_{df=2,18} = 21.6$, $p < 0.001$). Stream order had no effect on average mean daily water temperature ($F_{df=2,18} = 0.283$, $p = 0.757$) or on average maximum and minimum daily temperatures.

The average range in daily stream water temperatures was greatest for first-order streams (2.8 °C), least for second-order (1.9 °C), and intermediate for third order streams (2.4 °C). Stream order had no effect on the range in stream water temperatures ($F_{df=2,18} = 0.748$, $p = 0.488$). The range in daily stream water temperatures was greatest during the spring season (3.0 °C), intermediate during the summer season (2.5 °C), and least during the fall season (1.6 °C). The effect of season on the range in daily stream water temperatures was marginal ($F_{df=2,18} = 1.931$, $p = 0.174$). There was no interaction effect on the range in daily water temperatures between stream order and season ($F_{df=4,18} = 1.138$, $p = 0.370$).

Over the course of the study, stream water temperatures were generally lower than air temperatures above the stream channel (Fig. 2). This pattern was true for the spring and summer sessions, but reversed during the fall session. However, the difference was minor, even when evaluated by season ($F_{df=2,36} = 1.311$, $p = 0.282$). Mean, minimum, and maximum stream water and channel air temperatures were correlated (Table 5). Correlations generally increased with increasing time scale (i.e., hourly, daily, weekly). Temperature correlations were strongest in the fall, intermediate in the spring, and lowest in the summer. Air-water temperature correlations were slightly less for first-order streams than for second- and third-order streams.

3.6. Percent soil moisture

No discernable pattern was observed for the effects of riparian location on percent soil moisture ($F_{df=6,55} = 0.508$, $p = 0.799$; Fig. 4). Soil moisture percents were frequently highest at the bank location but not consistently so. Stream order appeared to have some effect on soil moisture ($F_{df=2,55} = 5.104$, $p = 0.009$); average percent soil

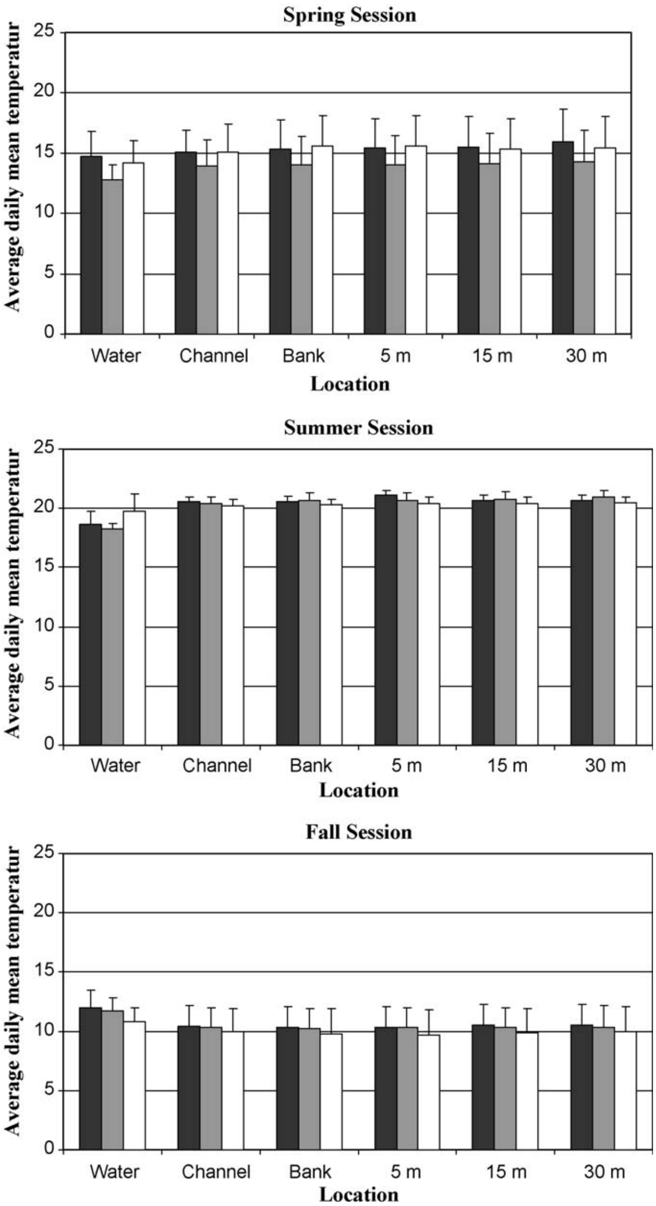

Fig. 2. Average, with standard error, daily mean air temperature (°C) by season, stream order (first order – black, second order – stipple, third order – white), and riparian location, and average daily stream water temperature by season and stream order, Quabbin Reservoir watershed, Massachusetts, 2008.

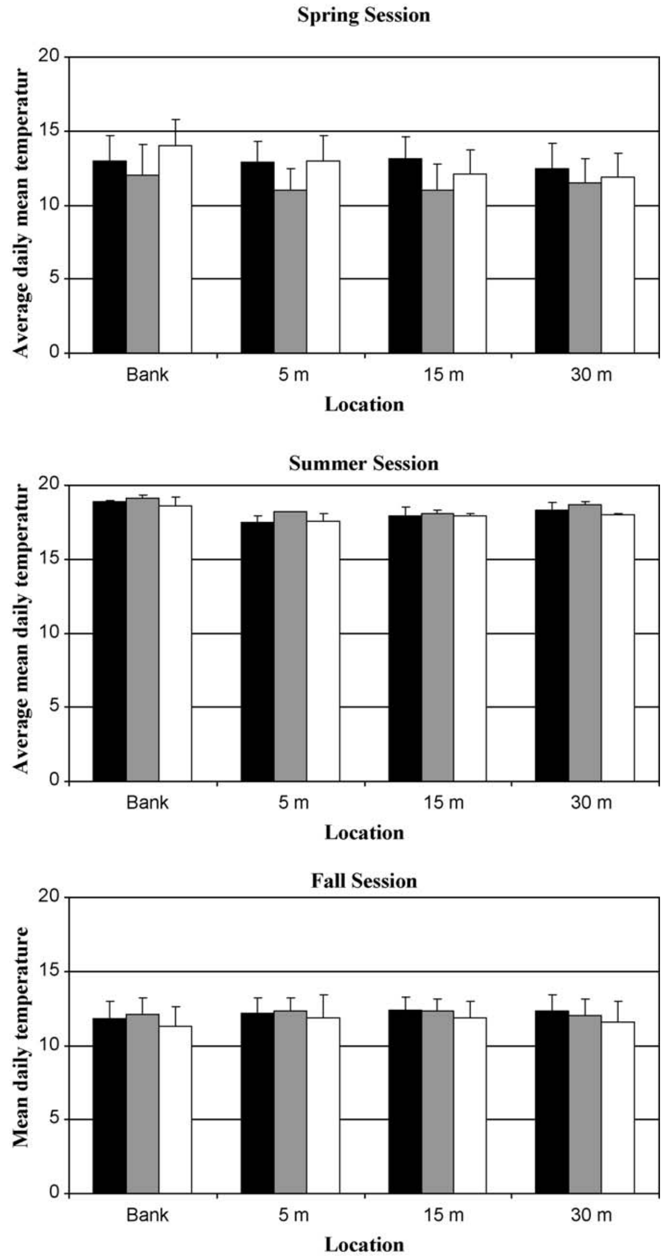

Fig. 3. Average, with standard error, daily mean soil temperature (°C) by season, stream order (first order – black, second order – stipple, third order – white), and riparian location, Quabbin Reservoir watershed, Massachusetts, 2008.

Table 5
Correlations between hourly air and stream water temperatures and daily and weekly average maximum, minimum, and mean air and stream water temperatures, Quabbin Reservoir watershed, Massachusetts, 2008.

	Hourly temperatures	Daily			Weekly		
		Maximum temperatures	Minimum temperatures	Mean temperatures	Maximum temperatures	Minimum temperatures	Mean temperatures
Overall	0.739	0.638	0.858	0.777	0.879	0.929	0.913
By stream order							
First	0.612	0.486	0.780	0.631	0.835	0.938	0.897
Second	0.838	0.843	0.887	0.885	0.924	0.923	0.912
Third	0.840	0.845	0.915	0.907	0.913	0.937	0.914
By season							
Spring	0.483	0.374	0.634	0.492	0.668	0.820	0.736
Summer	0.430	0.368	0.441	0.286	0.332	−0.121	0.185
Fall	0.797	0.740	0.893	0.877	0.949	0.937	0.956

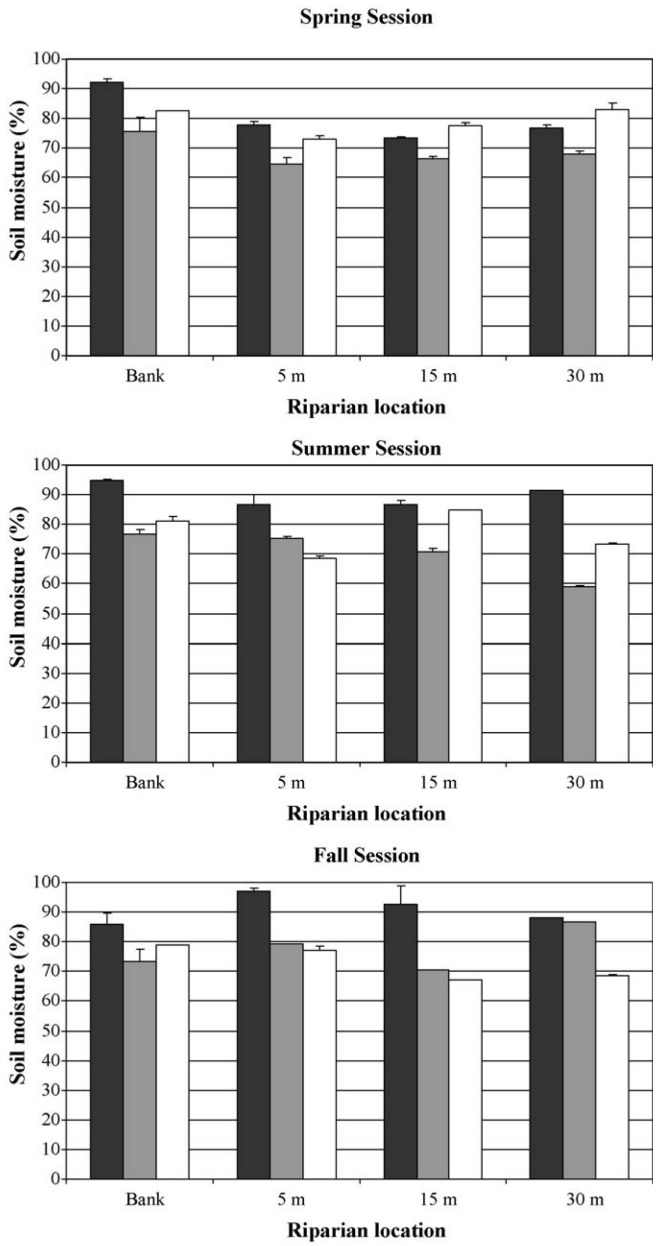

Fig. 4. Average, with standard error, soil moisture (%) by season, stream order (first order – black, second order – stipple, third order – white), and riparian location, Quabbin Reservoir watershed, Massachusetts, 2008.

moisture was generally greater at first-order stream riparian locations than at those locations on second- or third-order streams.

4. Discussion

Riparian zones along forest streams provide a diversity of products and amenities, principally the protection of water quality and aquatic habitats (Verry et al., 2000; Ekness and Randhir, 2007). In addition to the increased biological diversity inherent in the juxtaposition of aquatic and terrestrial habitats (Crow et al., 2000; Sabo et al., 2005), riparian zones have been shown to be unique from adjacent upland forest. Differences in vegetative composition (Goebel et al., 2003; Hagan et al., 2006) and in use by invertebrates (Rykken et al., 2007b), amphibians (Pauley et al., 2000; Perkins and Hunter, 2006; Crawford and Semlitsch, 2007), birds (DeGraaf and Yamasaki, 2000; Bub et al., 2004) and mammals (DeGraaf and Yamasaki, 2000; Ford et al., 2006) have been reported. The unique habitat qualities of riparian zones have been ascribed, in part, to their microclimatic conditions (Brosofske et al., 1997; Moore et al., 2005; Olson et al., 2007; Rykken et al., 2007a).

Biological evidence for the existence of a unique riparian zone along low-order streams in northeastern forests is limited. Perkins and Hunter (2006) used amphibian richness and abundance to define a narrow (7–9 m) riparian zone along 15 headwater (first order) streams in northwestern Maine. Hagan et al. (2006) surveyed vascular plants along the same 15 streams and identified a compositionally different and more rich herbaceous plant community within 5-m of stream edges. They attributed this narrow plant-defined riparian zone to the highly incised nature (17% lateral gradient at 10-m) of the streams restricting lateral flooding and the development of fluvial landforms. Osbourne et al. (2005) were unable to identify a unique or different small mammal community between riparian and upland forest in West Virginia. Williams and Moriarity (1998) identified a riparian flora, richer in forbs and ferns than upland forest, along four small streams in northwestern Pennsylvania. None of these studies appeared to have recorded microclimatic conditions.

Stewart and Mallik (2006) reported a significant decline in plant cover (canopy, shrub, and ground) with distance from stream edges in conifer forest in Ontario, Canada. However, the greatest change at undisturbed forest sites was across the non-forested riparian – forest ecotone at 10 m from the stream edge. There appears to be no change in cover with distance beyond the ecotone out to 60 m. Microclimate conditions also changed with distance from streams in this study. Air temperature and vapor pressure deficit increased slightly with distance, while relative humidity decreased slightly with distance. Soil moisture decreased strongly with distance out to 30 m.

Unlike western U.S. studies of riparian microclimate (Brosofske et al., 1997; Anderson et al., 2007; Richardson and Danehy, 2007; Rykken et al., 2007a), we were unable to document the existence of gradients in either air or soil temperatures or soil moisture within 30-m of first- to third-order streams in southern New England forests (Figs. 2–4). Further, we are unaware of any published study of the existence of riparian microclimates in northeastern U.S. forests. Hagan and Whitman (2000) measured air temperatures at 10-m spacing, 50 m into intact riparian forest on a first-order stream in western Maine. No gradient in air temperatures was observed along the uncut control forest transect (J. Hagan, Manomet Center for Conservation Sciences, Brunswick, ME; personal communication). Stewart and Mallik (2006) described the near-ground microclimatic gradient extending from the streams into the undisturbed upland forest at their Canadian sites as relatively subtle.

From this study and the few other published riparian evaluations, it appears that the existence of a unique riparian microclimate along low-order streams in northeastern forests is questionable. The temperate, humid conditions of this region are such that the presence of a stream appears to have no moderating effect on adjacent forest-floor temperatures (Figs. 2 and 3), soil moisture (Fig. 4), or woody-stemmed vegetation structure or composition (Table 3). We did not assess atmospheric moisture across the riparian zone. It is likely, even under the humid conditions we experienced, that the presence of free flowing water would increase atmospheric moisture, if only at the stream banks immediately adjacent to the stream channel (Brosofske et al., 1997). This attribute should be included in future riparian microclimatic studies.

While this study was conducted over only one year, the relationships between controlling variables and forest-floor temperature and soil moisture are based mostly on physical principles. Repeating the study over three seasons (sessions) provided data from a range of weather conditions. While additional surveys would likely broaden the range of measured conditions, the relationships would remain constant and the results should only be strengthened.

The full set of 27 stream segments was not surveyed concurrently, which allowed for temporal variability in the controlling variables among surveys. Concurrent surveys of all 27-stream segments would have required more data loggers than budgets allowed. However, each 8-day survey included a randomly selected first, second, and third order stream segments, allowing for the direct comparison of the effects of stream order and distance on forest-floor temperature and soil moisture. The sampling design we used was a compromise between fiscal reality and the desire to include a wide range of riparian conditions.

The conclusions of this study need to be reaffirmed in other locations and in other forest conditions. The forests of the Quabbin, and those along our streams, are typically second growth with a limited age distribution (Kyker-Snowman et al., 2007). These mature forests have closed canopies (Table 3), allowing little solar radiation to penetrate to the forest floor (Reifsnyder et al., 1971/1972; Hutchison and Matt, 1977). If we had included a broader range of forest conditions, especially early successional or older forests with low, more open canopies or with canopy gaps, allowing for greater penetration of solar radiation or wind (Spurr and Barnes, 1980), perhaps a distinctive riparian zone with a characteristic forest-floor microclimate may have developed. Additionally, the riparian buffers along our streams are relatively level out to 30 m, with an overall average slope between the top of the bank and the 30-m location of about 8% (Table 2). A temperature and soil moisture gradient would be more likely along more highly incised streams such as those studied by Hagan et al. (2006), with a lateral slope of 17% at 10 m. Alternatively, if we had extended our upland locations further from the stream, and presumably at greater elevations above the stream channel, we may have identified a distinctive riparian microclimate.

While we were unable to identify a distinctive riparian-zone microclimate, we did find a strong relationship between air and stream water temperatures. The correlations were strongest for minimum air and water temperatures and for longer time scales (weekly > daily > hourly) (Table 5). The strength of these relationships supports the use of projected air temperatures for the assessment of the potential effects of climate change on southern New England streams (Pilgrim et al., 1998; Mohseni and Stefan, 1999; Morrill et al., 2005).

5. Conclusions

Riparian zones, however defined, are considered an important contributor to forest biodiversity. The existence of a unique riparian zone, based on distinctive microclimate and floral and faunal communities has been repeatedly demonstrated for more arid, western conifer forests. The existence of similarly unique riparian zones in more mesic, eastern deciduous forests are uncertain, the research inconsistent. This study does nothing to change this observation, failing to identify distinctive forest-floor temperature or soil moisture patterns across a 30-m riparian zone along low-order streams in southern New England.

Despite the lack of a different riparian microclimate, and of uncertain floral or faunal riparian communities in northeastern forests, it is nevertheless critical that riparian zones be recognized and protected during harvesting operations or other disturbance events (Phillips et al., 2000; Lee et al., 2004). While these forests may not be unique from adjacent upland forest, at least in terms of forest-floor microclimate, it is beyond argument that protection of the riparian buffer is critical to the protection of forest streams and the services they provide to forest health and biodiversity.

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